# Measuring the Weak Nuclear Force between Protons and Neutrons

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## Introduction

A team of scientists from Physics Division, the University of Indiana, UC Berkeley, the Joint Institute for Nuclear Research-Dubna, the University of Michigan, the University of New Hampshire, the KEK National Laboratory-Japan, and the National Institute of Standards and Technology is developing an experiment to answer long-standing questions concerning the weak interaction of nucleons. This experiment will be done at the LANSCE spallation neutron source using cold polarized neutrons. The pulsed cold-neutron beam line is being constructed now and data collection is scheduled to begin in summer 2003. In this report, we describe the physics goals of the experiment and technical progress on the apparatus to do the experiment. We have recently completed tests of a one-tenth-scale prototype of the apparatus and validated the performance of the design using a pulsed cold-neutron beam.

Nucleons are bound together to form nuclei by the strong interaction. Both nucleons and nuclei decay through the much more feeble weak interaction. For example, a neutron decays into a proton, an electron, and an electron anti-neutrino. The existence of weak decays of nucleons implies that pairs of nucleons interact weakly as well as strongly. The strong interaction is invariant under the parity transformation, reflection in a mirror. The signature of the weak interaction is parity-violation. This signature will be used to experimentally isolate the small effects from the weak interaction in the presence of the much stronger (10 million times) strong interaction. Examples of phenomena that result from the small parity-violating weak force between nucleons are the existence of static anapole moments in the ground states of nuclei such as cesium-133, circular polarization of photons from transitions between states of unpolarized nuclei, parity-odd correlations from photons emitted from polarized nuclei, and large parity-violating longitudinal asymmetries of the total cross sections for compound-nuclear resonances. Although scores of parity-violating asymmetries have been observed in nuclei, a quantitative description of these measurements has yet to be developed. The goal of this experiment is to unambiguously determine the most important coupling constant in the potential that describes the weak force between nucleons. The modern theory of weak and strong interactions is known as the standard model. The weak interaction of nucleons involves the basic constituents of the standard model and is shown diagrammatically in Figure 1.

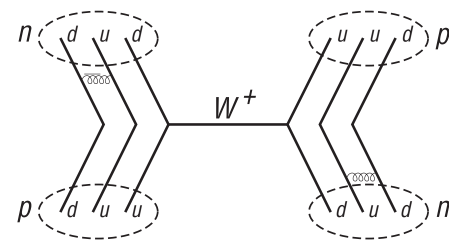


**Figure 1. Two nucleons exchange a vector boson.**

Each of the two nucleons is made up of three quarks. Two quarks bound in different nucleons interact weakly through the exchange of a vector bosons, the $W^+$, $W^-$, and $Z^0$. The weak couplings of quarks have been well determined through experiments in nuclear and high-energy physics. Because of the properties of the strong interaction, the above picture must be modified. The strong interaction between nucleons is mediated by the exchange of mesons, each consisting of a pair of quarks. The light pi ($\pi$) meson produces a long-range attractive force and the heavier rho ($\rho$) and omega ($\omega$) mesons produce a repulsive short-range force. The short-range repulsive strong interaction between nucleons prevents pairs of nucleons from getting closer than one Fermi (Fm), $10^{-13}$ cm. The vector boson exchanged between quarks is very heavy, 100 GeV, and at the momentum transfers characteristic of the interactions of pairs of nucleons in nuclei, is highly virtual. The range of the vector bosons is approximately $10^{-2}$ Fm, much shorter than the distance between nucleons. How then can the nucleons interact weakly? The same mesons that mediate the strong interaction also can mediate the weak interaction and bridge the distance between nucleons. The strong and weak interactions between nucleons are illustrated in Figure 2.

The light, 0.14 GeV, $\pi$ meson is much less virtual than the heavier vector bosons, and provides for a range of the weak interaction between nucleons the same as the strong interaction, ~1 Fermi. This picture of the weak interaction of nucleons is known as the meson-exchange model, and is characterized by a number of nucleon-nucleon-meson couplings. The most important of these is the long-range $\pi$-nucleon-nucleon weak coupling.

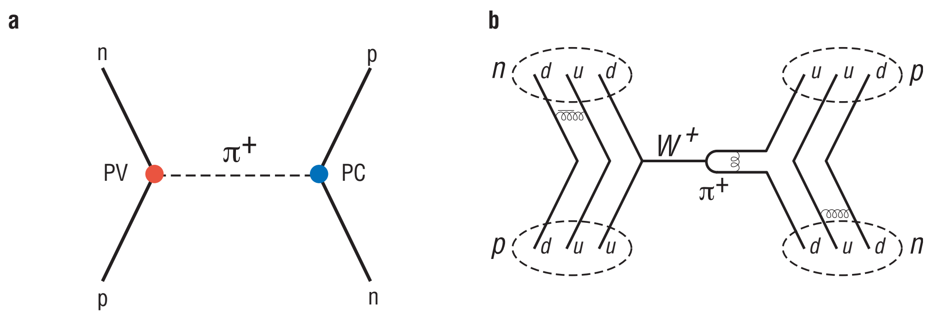


**Figure 2. (a) Two nucleons exchange a $\pi$ meson. (b) One nucleon emits a $\pi$ meson strongly, the $\pi$ turns into a W, and the W scatters from a quark in the other nucleon.**

## Not So Clear a Picture

The picture painted above does result in some difficulties of interpretation. First, the quarks that interact in Figure 2b are not free, but are bound in nucleons. The couplings between quarks and vector mesons are appropriate for free quarks. The strong interaction between quarks is carried by gluon exchange, shown as curly line in Figure 2b. The exchange of gluons between quarks modifies the weak couplings between quarks and vector bosons, and the weak couplings between nucleons are different than those of free quarks. In principle, these modifications can be calculated in the standard model, which describes the strong as well as the weak interactions of quarks. However, at present the strong interaction can be treated only at very large momentum transfer in a framework known as perturbative quantum chromodynamics (QCD). In order to describe phenomena involving weak interactions of nucleons, the weak couplings shown in Figure 2b must be determined experimentally.

The second difficulty arises because nuclei are many-body systems and the many-body problem can not be solved in general. In order to determine the meson-nucleon-nucleon couplings, it is necessary to know the wave functions that describe the initial and final states for the process being observed. The weak interaction between the nucleons can be treated as a perturbation between the states that result from solving the many-body strong-interaction problems. Experimental observables can be expressed as matrix elements of the operators describing the meson-nucleon-nucleon interaction and weak meson-nucleon-nucleon couplings. Because the many-body strong-interaction can not be solved in general, attempts to interpret the results of experiments have depended on model wave functions. The observation of a parity-violating asymmetry in the two-body neutron-proton system does not suffer from this difficulty because the two-body strong interaction problem can be solved exactly.

## Our Experiment

In the experiment, a polarized cold neutron beam is stopped in a liquid-hydrogen target. The neutrons capture on the protons to form deuterium (D) nuclei with the emission of a 2.2 MeV photon. If parity is conserved, the direction of emission of the photon is isotropic with respect to the neutron polarization, *s*. The connection between parity violation and isotropy is shown in Figure 3. Under mirror reflection, the vector, *k*, that describes the photon direction does not change. However the pseudo vector, *s*, that describes the neutron spin direction or handedness does change. When reflected in the mirror the direction of rotation, shown by the rotating arrow, changes handedness, much as a person's left and right hands are interchanged in his mirror image.

The experiment isolates the isovector weak pion-nucleon-nucleon coupling, $H_{\pi,1}$. The (somewhat simplified but correct) reasoning is as follows. The transition between the initial scattering state and the deuteron ground state has a magnetic-dipole or character. If the deuteron wave function has a parity impurity, an electric-dipole transition can occur between the initial scattering state and the odd-parity component of the deuteron. The transition operator has an isovector character. The scattering state and deuteron ground state both have isospin 0, and can not be connected by the isovector transition operator. The weak interaction between nucleons has isoscalar, isovector, and isotensor parts. The isovector transition operator connects only isovector admixtures to the isoscalar deuteron scattering state. The weak interaction between nucleons has isovector contributions from the $\pi$, $\rho$, and $\omega$ mesons. The $\pi$ is lighter than the $\rho$ and $\omega$ mesons and the interaction it carries has a longer range than the others. The deuteron is very weakly bound and the two nucleons are far apart. Only the long-range $\pi$ component of the weak nucleon-nucleon interaction makes a significant contribution to the transition amplitude.

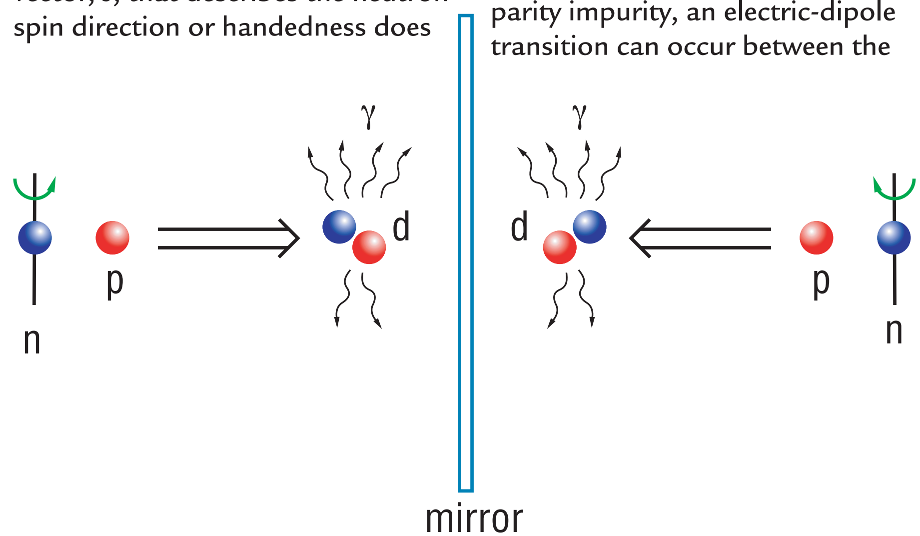


**Figure 3. Mirror images of photon emission.**

The apparatus, shown schematically in Figure 4, consists of a cold-neutron source, followed by a neutron polarizer, and a liquid para-hydrogen target, surrounded by an array of gamma-ray detectors. Neutrons from the spallation source are moderated by a liquid-hydrogen moderator. The source is pulsed, thus allowing measurement of neutron energy through time-of-flight techniques. The neutron guide transports the neutrons from the moderator through the biological shield with high efficiency. The neutrons are then polarized in the vertical direction by transmission through polarized helium-3 gas. The neutron spin direction can be subsequently reversed by the radio-frequency resonance spin flipper. The use of this type of a spin flipper is only possible at a pulsed neutron source. The use of this spin flipper reduces the systematic error associated with spin-dependent deflection of the neutron beam due to the interaction of the neutron magnetic moment with magnetic field gradients. The neutrons are captured in the target, which consists of liquid para-hydrogen. This state of hydrogen is required because neutrons depolarize quickly in ortho-hydrogen, while those with energies below 15 MeV retain their polarization in para-hydrogen. Gamma rays emitted in the capture process are detected in the cesium-iodine(thallium) detectors surrounding the target. The light of scintillation for these detectors is converted to an electrical current by vacuum photo diodes and amplified by low-noise preamplifiers. The parity-violating asymmetry causes an up-down asymmetry in the angular distribution of the gamma-rays for vertical neutron spin. When the neutron spin is reversed, the up-down gamma-ray asymmetry reverses.

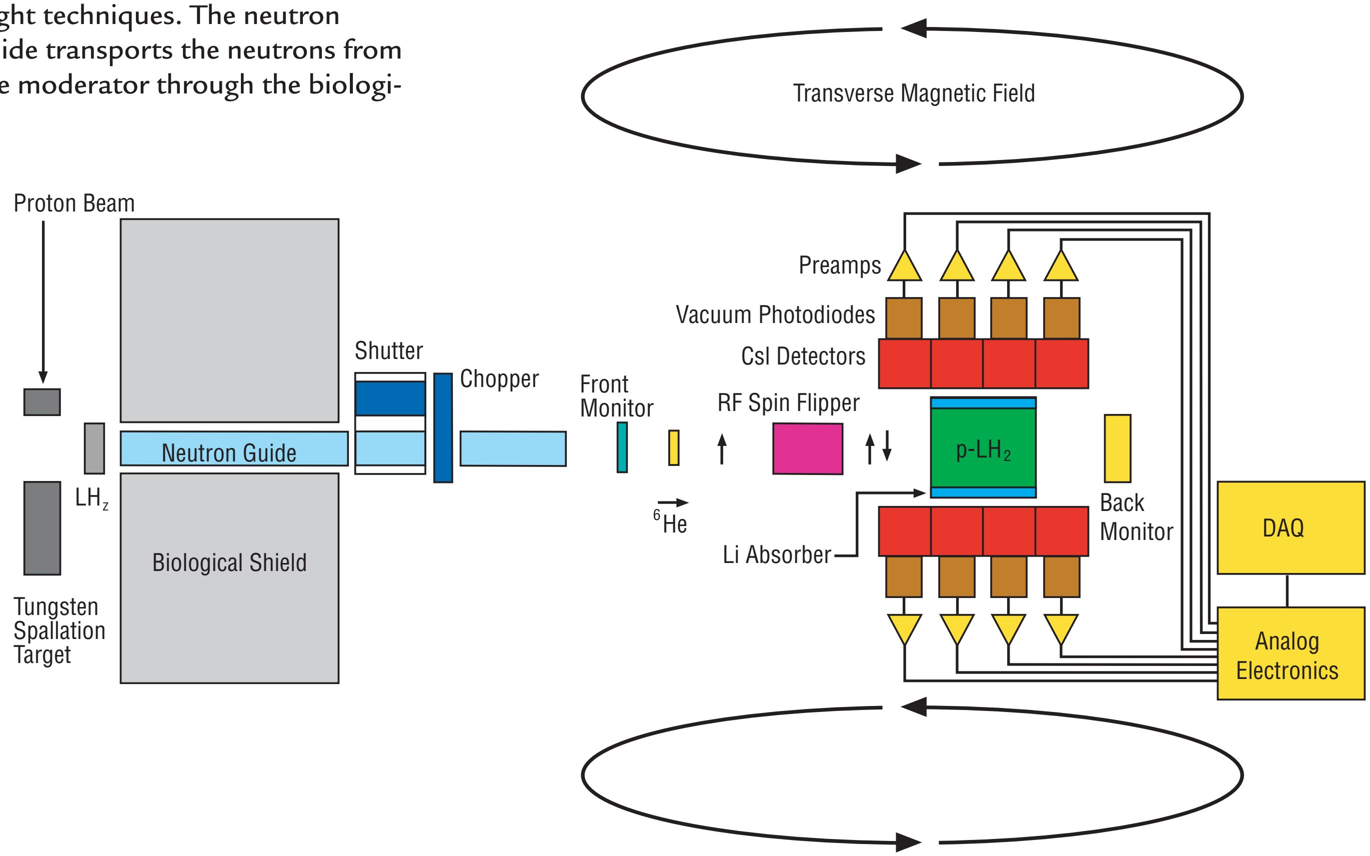


**Figure 4. A schematic of our experimental apparatus.**

## Experimental Results

In 2000, we conducted a test run using a one-tenth-scale prototype of the experiment at an existing cold neutron beam line at LANSCE. The test include a polarized helium-3 neutron polarizer, the radio-frequency neutron spin flipper that will be used in the final experiment, four of the 48 cesium-iodine gamma-ray detectors that will be used in the final experiment, and ionization chamber beam monitors. Instead of a liquid hydrogen target, we used nuclear targets that have known parity-violating asymmetries.

Review committees had identified the helium-3 polarizer and the radio frequency neutron spin flipper as the most challenging technological problems in the experiment. The neutron polarization produced by the polarized helium-3 cell was in quantitative agreement with the expected performance although the size of the test cell was smaller than required for the final experiment. Since the test run was completed, our collaborators have successfully produced a 12-cm-diameter polarized helium-3 cell and demonstrated 50% helium-3 polarization. We expect further improvements in cell performance, but the 12-cm-diameter cell is adequate to do the experiment. The radio frequency spin flipper had a measured efficiency for reversing the neutron spin of 97%. This efficiency corresponds very well with our design calculations.

We performed a careful measurement of the cold neutron flux from the liquid hydrogen moderator. We found that the measured flux was 10% higher than the predictions of the Monte Carlo simulation used by the designers of the neutron source. Thus, we expect that the neutron flux in the beam line we are building will be adequate for the experiment. In most nuclear-physics experiments radiation produces pulses in detectors that is counted by digital electronics. The error, $\Delta n$, in the number of detected radiation quanta, n, is given by Poisson statistics $\Delta n = \sqrt{n}$. The cesium-iodine gamma-ray detectors operate by converting gamma radiation into light that is converted to a current signal by vacuum photodiodes. The small current is amplified by low-noise preamplifiers and linear amplifiers and recorded by transient digitizers. We have taken this approach because the rates at which gamma quanta are detected, ~$10^{10}$ Hz, is too great to be counted by digital electronics. We measured the response of the cesium-iodine detectors and photodiodes, number of photo electrons/gamma quantum, to be 1000 photo electrons/gamma quantum. This yield is two times larger than the design goal of the experiment and should allow us to attain the counting statistics limit. In order to test our ability to attain the counting statistics limit we measured the parity-violating asymmetries produced by a number of nuclear targets, lanthanum-139, chlorine-35, and cadmium. The measured asymmetries agreed well with the previous measurements. The observed statistical errors corresponded to our expectations. When we scale the observed errors to the neutron beam intensity, neutron polarization, and detector solid angle of the final experiment, we obtain the design statistical error. On the basis of the test-run results, we are confident that the experiment will run as designed and provide a valid and statistically significant measurement on the parity-violating asymmetry in the $n + p \rightarrow d + \gamma$ reaction and a determination of the weak isovector pion-nucleon coupling.